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Solid Lubrication for Spacecraft Mechanisms

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13. ABSTRACT (*Maximum 200 words*)

Solid lubrication is critical for many moving mechanical assemblies (MMAs) on spacecraft in applications where containment of liquids is a problem, and where extremes of temperature are involved. Successful applications include deployment mechanisms, antenna gimbals, solar array drive bearings, low-temperature scanner and gimbal bearings, cryogenic propellant valves, slip rings, and gears. The successful use of solid lubricants requires an understanding of their materials properties, and of which solid lubricant formulation is best for the chosen application. Issues such as substrate surface pretreatment, materials compatibility, and potential debris generation must be taken into account during the design of a lubricated device. Testing of the lubricated part should include duplication of flight conditions. Although MoS_2 has been the most useful solid lubricant for spacecraft MMAs, care must be taken to minimize humidity during terrestrial storage and operation of MoS_2-lubricated devices.

14. SUBJECT TERMS Solid Lubrication Spacecraft Lubrication Molybdenum Disulfide (MoS_2) Wear Resistance	Polytetrafluoroethylene (PTFE, or Teflon) Self Lubricating Materials Tribology Friction	15. NUMBER OF PAGES 54
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1. Introduction

The main purpose of lubrication is to prevent direct contact of two surfaces in relative motion. In the space vacuum environment, where oxygen, moisture, and ambient hydrocarbons are not available to adsorb on surfaces and provide protective molecular-level coatings, lubricants are necessary to prevent damage from galling, friction, and wear processes. The type of lubricant (solid or fluid) can be selected based on the anticipated conditions of motion. Solid lubricants (as thin films or powders) are typically used for:

- Low to medium numbers of duty cycles
- Moderate to low contact stresses
- Extreme environments

Occasional circumstances arise when solids can be used for high contact stress applications but only for a very short duration of motion, such as for an antenna release or deployment mechanism.

Fluid lubricants (oils and greases) are used in mechanisms with many cycles, either rotational (e.g., ball crossings in a ball bearing) or reciprocal sliding, where contact stresses are determined by the yield-strength properties of the load-bearing materials, and where the environment is relatively benign. In most cases of fluid lubricant use, the apparatus is engineered to confine the lubricant so that it is not lost from the critical contact regions by means of evaporation, creep, or centrifugal motion. For solid lubricants, it is also necessary to confine the lubricant in the contact region, but this task is easier because the physical mechanisms acting on them are different from those acting on fluids.

The system parameters that need to be considered and the methods for providing lubricant within the contact will be discussed in later sections of this chapter. In general, it is important that *any mechanical subsystem must be designed with full knowledge of*:

- Type of lubricant
- Material properties of the device surface
- Contact stress
- Type and duration of relative contact motion

It is not appropriate to design the apparatus and then "see the lube guy" for an appropriate oil or surface finish treatment. In the remainder of this chapter, we will discuss the history of solid lubricants, their materials properties and structures, deposition/fabrication processes, performance/applications, friction and wear testing, cautions, and future directions.

2. History

The history of solid lubrication probably goes back thousands of years, although its earliest recorded uses were within the last 200 years. For example, studies of graphite (previously known as black lead or plumbago) were conducted in the early 19th Century (1), and many patents involving lubricated devices were subsequently recorded (2). Another early solid lubricant, soapstone or talc, was used for lubrication of rotating axles in 1885 (2).

One early use of molybdenum disulfide (MoS_2) was by pioneers traveling through the Climax, Colorado, area in the 19th Century, where they used pulverized rock containing molybdenite ore to lubricate the wheels on their Conestoga wagons (3). The low friction of fluorocarbon-based polymers was explored beginning in the 1940s with the development of Teflon® PTFE (polytetrafluoroethylene). PTFE is now produced by other companies. The development of other low-friction fluorocarbons followed in the 1950s and 1960s, including fluorinated ethylene propylene copolymer (FEP), polychlorotrifluoroethylene (CTFE), and polyvinylidene fluoride (PVF) (4).

The use of bonded solid film lubricants containing graphite started in the 1940s in the aircraft industry (3,5). Soon after, MoS_2 was studied for use with binder materials such as corn syrup, asphalt-base varnish, silicon-base varnish, and glycerol (6). As the space program took off in the 1950s, the use of bonded MoS_2 lubricant films accelerated. Binder materials that do not outgas in the vacuum of space were required, including organic binders such as thermosetting resins, and inorganic binders including silicates and phosphates (5). Bonded PTFE films were also introduced during this period (7). The need for increased film adhesion and decreased film thickness was met beginning in the late 1960s with the development of sputter-deposited MoS_2 films (8).

Transition metal dichalcogenides (TMDs) other than MoS_2 started to be examined seriously in the 1960s (9,10). The attraction of other compounds was driven by the need for increased electrical conductivity and for increased resistance to oxidation at elevated temperatures in air. For example, TaS_2, $TaSe_2$, and WS_2 have greater oxidation stability at higher temperatures, while TaS_2, $TaSe_2$, and $NbSe_2$ have greater electrical conductivity. The use of these synthetic dichalcogenides has been precluded by their performance, which has not proven consistently superior to that of MoS_2, and by uncertainties in composition and higher expense (11). Some exceptions are WS_2, which is used in unbonded thin films (e.g., Dicronite®) and composites, and $NbSe_2$, which is used in conductive lubricating composites.

3. Material Properties/Structure

Several authors have expounded on the advantages and disadvantages of solid versus fluid lubricants (12-14). Such properties are summarized in Table 1. The different types of solid lubricants discussed below–namely, lamellar solids, polymers, metal salts, and soft metals–all have specific attributes that make them good choices for particular applications. However, solids generally possess the ability to operate in extreme temperature environments with little or no contamination of surrounding critical surfaces (e.g., optics and thermal control surfaces). Also, they are unaffected by storage for long periods, provided they are maintained in an inert environment (e.g., to ensure low exposure humidity). General properties that make solids good lubricants are low shear strength, good adhesion to the surfaces to be lubricated, low abrasivity (i.e., they must be softer than the substrates), and thermodynamic stability in the application environment (15).

Materials properties of lubricating materials, such as yield and tensile strength, coefficient of thermal expansion, thermal and electrical conductivity, are beyond the scope of this report. Since lubricating materials usually consist of mixtures of species (e.g., bonded films and bearing cage materials), materials/engineering properties of the individual components may have little relation to the composite lubricant. However, there are standard reference texts that provide compilations of property data. For example, Reference 16 provides information on a variety of polymers, ceramics, steels, and other metal alloys. Table 2 should be helpful in identifying the names and chemistry of the compounds described.

The most widely used solid lubricants on spacecraft are films derived from the lamellar TMD MoS_2 and polymers such as PTFE. In some cases, these two materials are combined to form self-lubricating bushings or ball-bearing cages. (Cages are also commonly called retainers.) Both materials are characterized by very low sliding friction coefficients, typically in the 0.05-0.1 range, with values as low as ~0.002 for sputter-deposited MoS_2 films under optimum preparation conditions (17). In general, the reasons both materials lubricate well are similar: they provide very low energy, repulsive surfaces on opposing substrates that result in minimum dissipation of energy when the substrates rub against each other. However, the chemical structures, and hence the molecular origins of low friction, of the two materials are quite different.

3.1 Transition Metal Dichalcogenides - MoS_2

TMDs are lamellar solids consisting of layers of material with strong chemical bonds within the layers but weak physical-type (van der Waals) bonding between layers. MoS_2 is the most widely used TMD. These solids are easily cleaved to form platelets of material that can be extruded and that can conform to curved and irregularly shaped surfaces. Low friction is achieved because these layers of material readily slide over one another (see Fig. 1a). The atoms of one tiny platelet (crystallite) do not line up with those of adjacent platelets (which in crystallographic terms is known as incommensurability), and some repulsion between the platelets results (17,18). The lubrication process involves movement of many crystallites within the area of contact, with some transfer of particles from surface to surface. An analogy would be if someone stepped on a stack of papers and the pages slipped, causing the person's feet to slide. It should be noted that this behavior tends to make the material fail at a constant shear stress, and that the apparent coefficient of friction will thus decrease as the normal load is increased.

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Table 1. Comparison of Solid and Fluid Lubricants for Space Applications			
Solid Lubricants		**Fluid Lubricants**	
Advantages	Disadvantages	Advantages	Disadvantages
Negligible volatility	Life determined by lube wear - poor resupply systems	Resupply possible - long life	Finite vapor pressure - confinement req'd
Wide operating temperature	Friction sensitive to debris - torque noise	Low torque noise - good models for torque calculation	Physical properties sensitive to temperature
Accelerated testing possible if failure mechanism known	Life, friction can be air, moisture sensitive	Generally insensitive to air, moisture	Accelerated testing very difficult
Electrically conducting	Poor thermal conductance	Good thermal conductance	Poor electrical conductance
Substrate sensitivity*		**Substrate sensitivity***	

*For both solid and fluid lubricants the substrate can influence the performance. For solids adhesion can determine wear life, while for fluids antiwear and friction reducing additives can behave differently on different materials. These variations emphasize the need for careful design practices.

Table 2. Materials Discussed in this Report

Material Name	Chemical Formula	Abbreviations/ Other names
aluminum phosphate	$AlPO_4$	
aluminum metal	Al	
antimony oxide	Sb_2O_3	
argon gas	Ar	
barium difluoride	BaF_2	
boron atom	B	
calcium difluoride	CaF_2	Fluorite
carbon atom	C	
chromium metal	Cr	
fluorinated ethylene propylene copolymer		FEP
Freon 113	1,1,2-trichloro-1,2,2-trifluoroethane	Freon TF
gold metal	Au	
gold-cobalt alloy	Au(Co)	
gold-palladium alloy	Au(Pd)	
graphite fluoride	$(CF_x)_n$	
indium metal	In	
lead metal	Pb	
lead monoxide	PbO	
molybdenum metal	Mo	
molybdenum disulfide	MoS_2	molybdenite, moly
molybdenum trioxide	MoO_3	
nickel	Ni	
niobium diselenide	$NbSe_2$	
nitrogen atom	N	
nitrogen gas	N_2	
phosphorus atom	P	
polychloro-trifluoroethylene		CTFE
poly(aryletherketone)		PEEK
polytetrafluoroethylene		PTFE, Teflon®
polyvinylidene fluoride		PVF
silicon nitride	Si_3N_4	
silver metal	Ag	
silver sulfide	Ag_2S	
sodium silicate	Na_2SiO_3	
sulfur atom	S	
sulfuric acid	H_2SO_4	
tantalum disulfide	TaS_2	
tantalum diselenide	$TaSe_2$	
tin metal	Sn	
titanium metal	Ti	
titanium carbide	TiC	
trichloroethylene		TCE
tungsten disulfide	WS_2	tungstenite
zirconium dioxide	ZrO_2	

(a) MoS₂ Lubrication

(b) PTFE Lubrication
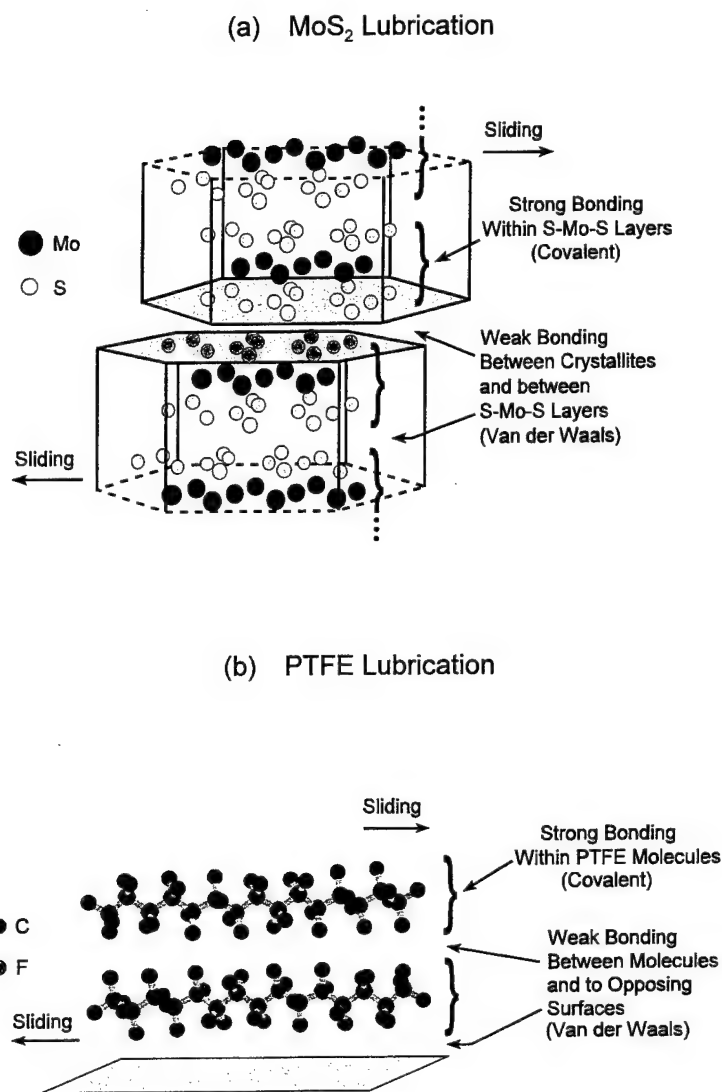
Figure 1.   Molecular origins of low friction in lubricants based on (a) MoS₂ and (b) PTFE. Both structures rely on reduced dimensionality for low friction. MoS₂ exists in a pseudo-two-dimensional structure consisting of stacked S-Mo-S "sandwich" layers. There is strong covalent bonding within the sandwich layers, but relatively weak van der Waals bonding between these layers. Lubrication occurs because crystallites in contact with one another are incommensurate, i.e., the *a* and *b* crystallographic directions are different for the two crystallites, while their *c* directions are in approximate alignment. Lubrication with PTFE is similar in that pseudo-one-dimensional chains exhibit strong covalent bonding within a chain, and weak van der Waals bonding between a chain and either other chains or a contact bearing surface.

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Other TMDs can be used in spacecraft lubrication. Their relative performance is primarily related to subtle differences in their crystal and electronic structures. For example, WS_2 is a good lubricant; it has virtually the same structure as MoS_2 because W is in the same group as Mo in the periodic table. Similarly, $MoSe_2$ is a good lubricant, since S is in the same group as Se. However, MoS_2 has proven consistently superior to WS_2 and $MoSe_2$ at typical operating temperatures. This superiority may be due to the less diffuse orbitals on the smaller Mo and S atoms, resulting in a surface with poorer bonding properties. Such poorer bonding gives rise to lower shear force and friction.

When TMDs are formed from metals in neighboring groups–for example, to give TaS_2 and $NbSe_2$–solid lubricants result, but with decidedly poorer tribological properties than Mo- and W-based TMDs. Because Nb and Ta have one fewer d-electron than Mo and W (respectively), the resultant TMDs are semimetals (i.e., have unfilled valence bands). In contrast, MoS_2 and WS_2 are semiconductors (i.e., have filled valence bands). The result is stronger interlayer bonding for TaS_2 and $NbSe_2$, resulting in higher shear strength and higher friction. However, the stronger bonding in Ta- and Nb-containing TMDs results in better high temperature behavior, while the unfilled valence bands result in higher electrical conductivity, so they are useful for specialized applications.

3.2   PTFE

PTFE is a crystalline polymer material consisting of arrays of long "zigzag" chains or helixes that are held together by primarily physical forces. The bonding within the chains is covalent and strong, while that between chains is weaker, providing a one-dimensional analog to the two-dimensional lamellar TMDs (see Fig. 1b). Highly electronegative, bulky (compared to hydrogen atoms in polyethylene) fluorine atoms are bonded to the "backbone" carbon atoms, causing the molecular chains to twist into helixes. Like the layers in MoS_2, these helixes do not form chemical bonds to other atoms or molecules, resulting in a very low-energy (nonwetting), low-friction surface. (The classical example of this phenomenon is the beading water on the Teflon® surface.) The lubricating action of PTFE results from alignment of the molecular chains in the direction of motion and drawing out of chains into the contact region (19-21). Formation of uniform transfer films of aligned molecular chains occurs under conditions of low energy dissipation (i.e., slow speed, low loads), while high contact temperatures result in uneven, bulk transfer of essentially melted lumps of polymer. The ordered molecular films provide low, uniform friction (low noise) within the contact, while the lumpy films result in low friction but with nonuniform (i.e., noisy) behavior until the films are spread thin. Such films can be smoothed out with continued operation only if the temperature in the contact region is lowered, which is unlikely.

3.3   Effects of Structure on Performance: MoS_2 versus PTFE

Both MoS_2 and PTFE form transfer layers between lubricated and unlubricated surfaces. However, for MoS_2, there is constant transfer of platelets between contacting surfaces, while for PTFE, lubrication is primarily between the extreme layers of the two contacting surfaces (22). In practical (operational) terms, these differences mean that PTFE films may be more stable during storage and more durable during operation, providing the yield strength of the film is not exceeded by the load, or the PTFE film does not exhibit excessive cold flow during storage. However, PTFE films also tend to have rougher surfaces, resulting in noisier operation (torque noise) of

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precision parts. Conversely, MoS_2-lubricated bearings can operate with very low torque and torque noise, but long endurance may require resupply of the lubricant when the initial film is worn away from the immediate contact region. Often the resupply process, which involves transfer of material from accumulations outside the contact region, results in uneven film formation and subsequent noise (23,24). More discussion on this subject is presented in Section 5.

3.4   Soft Metal Films

Soft metal films, primarily those of lead, reduce friction in ball bearings by providing low-shear flow in the contact region during microslip. Typically, soft metal film lubrication occurs by shear within the film, rather than a surface transfer process, as is the case with MoS_2. One advantage of lead films over those of silver or indium is the unavoidable presence of PbO, a reputed good solid lubricant, within the films (see Fig. 2b).

Metal film lubrication must be applied by a process that ensures adequate adhesion to the substrate surfaces, to avoid immediate loss from the contact. A common method is vacuum deposition using the ion-plating process (25). Ion-plated lead films are used in mechanisms such as solar array drives in European satellites (14).

3.5   Bonded Films

Bonded films consist predominantly of two components, the lubricant and the binder. The lubricant is generally a powder that is dispersed within the binder material. The binder provides improved adhesion of the lubricant to the surface of the part and controlled wear of the lubricant film. Bonded films can be classified in terms of the type of binder, types of lubricants/additives, and the curing method (3-5,11,13). There are hundreds (and perhaps thousands) of bonded solid lubricant products available, with a wide range of lubricants, binder materials, and additives. Current binder materials include thermoplastic and thermosetting resins for lower temperatures, and ceramics and other inorganics (e.g., glasses) for higher temperatures.

Figure 2c shows, schematically, the structure of a bonded film. When the film is applied to the mechanical device, the lubricant particles are spread uniformly throughout the binder. However, when properly burnished/run-in, the surface of the film should consist almost entirely of the lubricant. In the case of bonded MoS_2 films, the surface layer consists of MoS_2 crystallites with their basal or (0001) crystallographic planes oriented along the top surface of the film. In addition, the binder allows controlled wear of the film. The wear must be low enough to provide lubrication over the lifetime of the part, but must be high enough to allow continuous replenishment of the lubricant to the sliding surfaces of the parts. In some cases, the binder simply holds the powder in place in the contact region during run-in, whereon a burnishing process provides the permanent lubricant film.

MoS_2 and PTFE are generally used as lubricants for bonded films, either alone or in combination. Graphite is a common additive, but not appropriate if used alone (see Section 7). Additional materials can be added to provide improved properties; examples include Sb_2O_3, PbO, and other proprietary formulations. Other additives are used to improve general film performance, such as corrosion inhibitors, which are useful if ground testing or extended ground storage is required. Also, some additives do not play a direct role in lubrication, but improve manufacturing efficiency
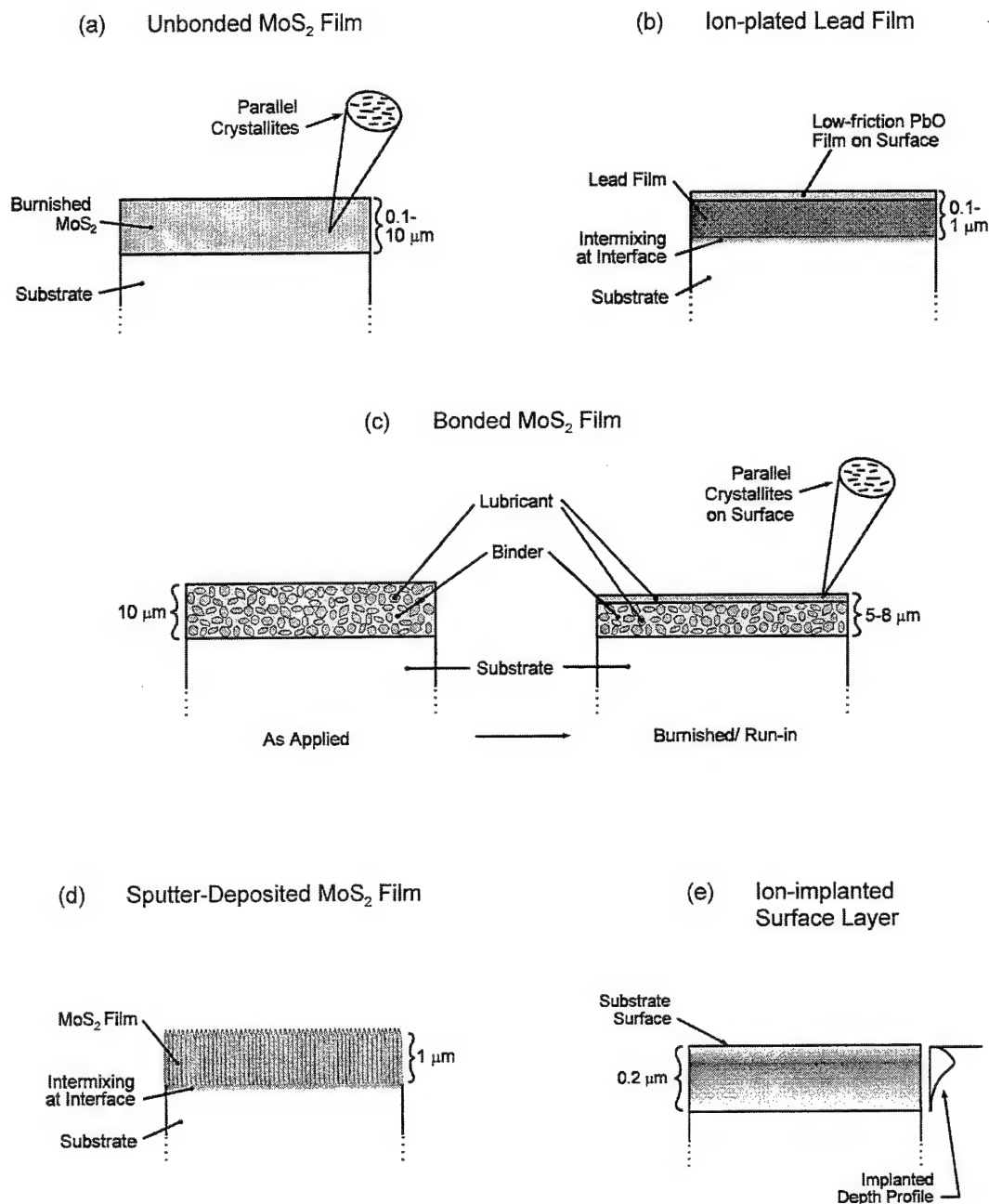
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Figure 2.   Cross-sectional schematic representations of the structure and thickness of solid lubricant films formed from (a) burnished unbonded MoS_2 powders, (b) ion-plated Pb, (c) MoS_2 powders mixed with an organic or inorganic binder, and (d) sputter-deposited MoS_2. Also shown is (e) an ion-implanted surface layer.

(e.g., dispersants, antisettling agents) and facilitate film application (e.g., wetting and flow agents).

For resin-bonded MoS_2 films, the optimum lubricant-to-binder ratio is in the range from 1:1 to 4:1, with 2:1 being typical. For sodium silicate bonded films, lubricant-to-binder ratios of 20:1 have been used. Higher lubricant gives reduced friction, but higher binder gives greater wear life, corrosion resistance, and hardness, with higher friction.

3.6 Composites/Self-Lubricating Materials

Self-lubricating materials in space mechanisms are used primarily as cage materials in ball bearings and as bushings. They generally contain the lubricants PTFE and/or MoS_2, and structural materials such as pure polymers [e.g., polyimides (26)], composites [e.g., PTFE with glass fiber reinforcement (13)], or metals (27). In low surface stress applications, PTFE can act as a self-lubricating material without the need for reinforcement. The best structural materials for minimizing wear are strong, but are softer than the bearing ball and race material.

The most common bearing cage composite for space applications is composed of PTFE and MoS_2 lubricant powders contained in a glass fiber matrix for reinforcement. Combining two lubricants seems to encourage optimum formation of transfer films. Metals used for bearing cages in space applications (at normal temperatures) provide reinforcement for the lubricant filler, but are usually softer than the steel bearings in which they are used. A common example is bronze, which is generally used with PTFE. Bronze/PTFE cages contain 20%-60% PTFE. Sometimes MoS_2 is used in addition to PTFE, but usually in smaller amounts (i.e., ~5%).

Thin PTFE lubricant films can be used with porous metal oxide films, such as anodize layers on aluminum. The intention is to impregnate the porous surface, to give a composite surface. The PTFE is the lubricant, and the anodize provides structural integrity.

3.7 Surface Reaction Layers

Mechanical devices made from soft or easily oxidized metals can be made more robust by the formation of surface reaction layers. Chemicals are reacted with the surface of the metal, to produce, for example, a metal oxide or metal phosphate layer. The reaction layers are harder than the metal and inhibit oxygen diffusion to the underlying metal surface. The formation of reaction layers on such metals is usually required before application of bonded solid lubricant films on their surfaces. (Although the bonded films provide a small amount of corrosion protection, it is usually not adequate.) Also, the reaction layer can lessen deformation of the underlying soft metal surface; such deformation can cause the lubricant film to weaken or debond.

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4.   Deposition/Fabrication Processes

In this section, processes and procedures are described for the application of the various types of solid lubricant to a variety of potentially contacting surfaces. Simply choosing the best solid lubricant formulation for an application is not adequate. Care should be taken to prepare the film correctly on the part's surface, since the structure and tribological properties of a given film can vary greatly. Failures have occurred in applications where the film preparation procedure was changed only slightly from a previously successful application.

4.1   Surface Pretreatment for Thin Lubricant Films

The surface(s) of the part or mechanism must be appropriately prepared before film application, primarily to increase the subsequent adhesion of the film. Surface cleanliness is necessary for all film growth techniques, since organic surface contamination can prevent strong bonding between film and substrate. Organic contamination is generally physically adsorbed to the part surface by van der Waals forces. Such forces are inadequate for forming a strong bond between the part surface and the subsequently applied lubricant film or coating.

Initial cleaning usually involves treatment with organic solvents and/or caustic cleaners. Previously, the solvent of choice was a chlorofluorocarbon like Freon 113® or a chlorinated hydrocarbon like trichloroethylene (TCE). However, because of the ozone-depleting potential of Freons®, and EPA volatile organic compound (VOC) limitations on TCE, alternate solvents are being developed. There has been some initial success using citrus-based cleaners. Also, perfluorinated solvents for cold- and vapor-degreasing are showing promise, including perfluorinated morpholines and perfluorinated cycloalkanes (28).

Depending on the specific type of lubricant film, additional pretreatment steps may be necessary. This is especially important for bonded films, which require surface roughening and either plating or passivation of the part surface, as discussed below. Even unbonded films (e.g., burnished MoS_2 powder) perform better with some surface roughness (3). However, it should be understood that a plot of endurance versus rms surface roughness has a maximum at a different position for applications with differing part material, film type, and even roughening method (e.g., grit-blasting versus grinding). As such, the optimum surface roughness must be found empirically for any nonstandard application.

4.2   Unbonded/Burnished Films

Unbonded lubricant films are usually fabricated from MoS_2, WS_2, or PTFE powders. The most common method is to burnish the lubricant powder onto a part's surface using a brush or cloth. The burnishing compacts the film and enhances the surface area of the substrate covered with film. This is important since the powders are usually bonded to the substrate surface by van der Waals forces; the more particles in contact with the surface, the better is the overall film adhesion. In the case of MoS_2 or WS_2, burnishing also causes orientation of the crystallites within the film such that the basal planes are mostly parallel to the sliding direction, allowing low friction (see Fig. 2a).

The powder can also be mixed with a volatile solvent for spraying, brushing, or dipping onto the part's surface. (In this case, burnishing can also enhance film performance.) The powder can be

sprayed onto the part's surface with an air blast gun at >100 psi pressure. Surface cleaning (as described above) is an important surface pretreatment requirement for burnished films. Organic contaminant film thickness is generally too great to allow short-range van der Waals bonding to occur.

For films formed by spraying MoS_2 or WS_2 powders under pressure, the part's surface may be further treated by roughening, usually with light abrasive grit blasting before film deposition. If necessary, the endurance of burnished films can also be enhanced by similar surface roughening, since the lubricant particles can be physically trapped within surface depressions, enhancing film adhesion.

4.3 Bonded Films

Appropriate surface pretreatment is critical for bonded films, since poor pretreatment can cause flaking and peeling of the film even before burnishing and subsequent use. Surface preparation procedures for bonded solid lubricant films are summarized in Table 3, and are discussed in more detail here.

Besides adequate precleaning (described above), surface roughening is done to optimize adhesion, although roughness should not be so high that abrasive wear occurs. This is commonly done by grit blasting using alumina, sand, or steel grit. Optimum surface roughness is in the range 20 to 35 μin rms, best achieved using 120 (29,30) or 220 (11) mesh alumina powder. The blasting pressure is usually in the range of 10 to 100 psi, depending on the substrate material (see Table 3).

Surface preparation must be allowed for, when determining part dimensions, since grit blasting and chemical etching can decrease part dimensions, while coating formation such as anodization can increase part dimensions. These processes can also result in increased surface roughness, potentially affecting tolerances. In addition, the thickness of the film must be taken into account in determining part tolerance budgets, since manufacturers cannot usually specify film thicknesses to better than ±0.1-0.2 mil (2.5-5 μm).

After cleaning and roughening, a final treatment is done to the part's surface, usually involving a coating (most metals) or passivation treatment (stainless steel). Coatings used vary, depending on the metal used in the part. For resin-bonded films, coatings include chromates, phosphates, or anodize. Similar pretreatments can be used for inorganic- and ceramic-bonded films. However, when such lubricants are to be used at elevated temperatures, phosphating and chromating are avoided because these precoating materials could decompose.

The normal recommended thickness range of bonded solid lubricant films is 0.2-0.7 mil (5-18 μm). If the film is too thick, it is more structurally weak and can flake or peel. If the film is too thin, premature failure can cause film rupture. In low load conditions (i.e., less than ~1 ksi), wear life increases with film thickness, while for higher loads (i.e., more than ~10 ksi), wear life tends to decrease with film thickness (31). As such, a thicker film of 0.5 to 0.7 mil (12.5-18 μm) is recommended for lower loads, while a thinner film of ~0.3 mil (7.5 μm) is more appropriate for higher loads (11).

Another class of solid lubricant films that can be thought of as bonded films are those formed by impinging or "blasting" a solid lubricant such as MoS_2 or WS_2 onto a surface with a small amount of a proprietary inorganic binder system. The purpose of the binder is to provide film cohesion and to enhance adhesion to the substrate (5).

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Table 3. Surface Pretreatments and Curing for Solid Film Lubrication[a,b]				
	Solid Film Lubricant Formulation			
Substrate	**Organic-bonded/ Heat Cured[c]**	**Inorganic-bonded/ Heat Cured**	**Organic-bonded/ Air Cured**	**Ceramic-bonded/ Heat Cured**
Steel (Not Stainless)	1. Abrasive Blast ($\leq$30 psi) 2. Phosphating or Sulfidizing 200°C	Similar to Resin-bonded/ Heat Cured; many films require 200°C cure, possibly precluding Al, Cr, Ni, Cu, and Mg substrates.	Similar to Organic-bonded/ Heat Cured, but without heat cure [Heat treatment usually required to meet ASTM E595-90 outgassing requirements (46)]	1. Abrasive Blast 2. Group IIA fluorides: 500-900°C Others: ~300°C Only for high-temperature materials/alloys. Not generally used for materials in left-hand column.
Stainless Steel	1. Abrasive Blast ($\leq$30 psi) 2. Passivation 200°C			
Aluminum	1. Anodize or 1. Light Abrasive Blast 2. Chromating 150°C			
Chromium & Nickel	Abrasive Blast ($\leq$10 psi) 200°C			
Titanium	1. Abrasive Blast 2. Phosphating or Anodize 200°C			
Copper and Copper alloys	1. Light Abrasive Blast 2. Bright Dipping or Chromating or 1. Oxide coating 150°C			
Magnesium and its alloys	Hard Anodize or Dichromate treatment 150°C			

[a] Solvent clean is the initial pretreatment for all films

[b] Maximum temperatures in cure cycles listed for heat-cured films

[c] Cure temperatures in this column generally represent phenolic resins. Other organic binder materials (with cure temperatures) include polyimide (300°C), alkyds (~20 °C), epoxies (20-232°C), silicone (260°C), acrylic (20 to 150°C), polyurethane (90°C), and polyphenylene sulfide (370°C).

4.4 Sputter-Deposited Films

Sputter-deposition generally uses a plasma struck between a substrate to be coated and a target comprising the coating material. This is accomplished inside a pumped vacuum chamber to achieve low pressures necessary for the plasma formation but also to minimize contamination from atmospheric impurities. Both direct current (DC) and radio frequency (rf) plasmas are used. The plasmas are controlled to allow a net transport of material from the target to the substrate. This net transport is controlled by varying the polarity and magnitude of the DC voltage, or by using diode-type arrangements to rectify the rf field. Some substrate material is "back-sputtered" during deposition, which results in some intermixing at the interface between the substrate and the film. As such, the films are highly adherent, which serves to increase wear life (see Fig. 2d). Rf sputtering is more versatile in that films can be deposited on electrically insulating materials. By using magnetron sources, increases in deposition rates and confinement of the depositing material can be achieved.

For sputter-deposited films, fine abrasive polishing is done to produce a smooth surface, followed by ultrasonic degreasing in appropriate solvents. There is some evidence that roughening the surface of coated parts can increase endurance of sputter-deposited MoS_2 films during operation (32). For 52100 steel coated with 1-μm-thick MoS_2 films, a plot of endurance versus surface roughness produced a curve with a maximum, similar to that for bonded films (discussed above). The optimum surface roughness was found to be 0.2 μm (center line average). Lesser but significant improvement in endurance was seen for sputter-deposited MoS_2 films on roughened titanium and silicon nitride substrates. For the metal substrates, the coefficient of friction was shown to decrease as surface roughness increased, probably due to decreased contact surface area.

Once the substrate is installed in the vacuum chamber, oxide and other contaminant films are removed by inert gas ion bombardment. Such ion bombardment is accomplished by using a dedicated ion gun, or by adjusting the plasma so that there is a net removal of material from the substrate rather than from the sputtering target. The effectiveness of the presputtering process for cleaning is again a function of the base pressure or cleanliness of the vacuum system. Recent studies have shown that chemical etching of the surface of a steel part can also improve film adhesion. The etching removes the oxide layer on the surface to expose the chemically reactive metallic species underneath (33).

MoS_2 is the most common sputter-deposited lubricant. Improvements in the tribological properties of sputter-deposited MoS_2 films have been achieved recently using intentional doping by cosputtering the MoS_2 with a metal such as Ni, Au, or other compounds. The two materials are generally deposited simultaneously from two separate targets. Multilayer structures can also be formed by alternating exposure to separate targets containing MoS_2 and an appropriate metal. This is most easily done by computer-controlling the deposition process, including control over the target power supplies and gas flow controllers.

Controlling the cleanliness of the gases introduced into the plasma, and also the cleanliness of the chamber, are both critical in controlling the purity of the films. As discussed in Section 5, the composition of sputter-deposited MoS_2 films is sensitive to relatively small amounts of water vapor in the chamber during deposition.

4.5 Metal Films

Thin metal lubricant films can be deposited by electroplating, evaporation, sputter-deposition, and ion-plating. In ion-plating, ionized metal atoms are produced by evaporating them into an inert gas plasma. The part to be coated is biased negatively, attracting the positively charged metal ions to its surface to form the film (34). The structural and morphological properties of the films can be tailored for conditions of use by changing the bias and power settings.

Surface preparation for ion-plated samples is similar to that for sputter-deposition. The sample is finely polished to produce a smooth surface, and is degreased. Also similar to sputter-deposition, the sample can be ion-cleaned in the gas plasma before film deposition to enhance the chemical bonding between the film and substrate.

4.6 Ion-Implantation

The surfaces of steel or other bearing materials have been bombarded with medium energy ions (i.e., ~50-200 keV ion energy), primarily to enhance corrosion resistance (35). However, tribological performance is also enhanced: wear is lowered by increasing surface hardness, but friction can also be lowered. The ions are implanted within a range of approximately 0-200 nm (0-8 μin.) into the surface by an ion accelerator (see Fig. 2e). Within that depth, the atomic concentration of the ions can be as much as 10-50 at%. Ions can also be implanted via plasma immersion ion-implantation (PIII) (36). A wide variation of materials can be implanted, including metal ions such as Mo, Sn, Pb, and In, as well as ions such as B, N, P, S, and C, and even inert gas ions such as Ar and Kr. The degree of tribological improvement is dependent on the substrate material, the implanted ion, and the ion energy and fluence (i.e., dosage). Typically, fluences of $\sim 10^{16}$ to 10^{17} ions/cm^2 are optimum.

4.7 Composite Materials

In manufacturing metal/solid lubricant composites, three technologies can be used (27): powder metallurgy, casting, and spray deposition. Powder metallurgy involves mixing the various components, followed by compacting at high temperatures, and then sintering. Larger and more spherical particles optimize mixing without segregation, as does the use of materials that have similar densities. Major problems during manufacture occur in the sintering process. Sweating during liquid phase sintering is corrected by the addition of appropriate additives, while poor strength in solid phase sintering is compensated for by mechanical alloying and sintering under pressure. Casting involves mixing a liquid metal with particles of lubricant. Squeeze casting forces the liquid metal through a preform of the particles using pressure. Another casting method involves stirring the liquid with the lubricant to form a slurry, which then is cast by gravity or pressure. Spray deposition involves spraying liquid metal and powders through an atomizer onto a substrate to form a desired shape. In general, PTFE- and MoS_2-containing composites are formed by powder metallurgy.

Also, PTFE may be applied onto porous surfaces such as anodized Al coatings. Generally, the anodize should be not be sealed prior to PTFE application. The PTFE (or TFE telomer) is dispersed in a volatile solvent and applied to the surface. If the substrate is not heat sensitive, it can be heated to the PTFE melting temperature. Melting the PTFE greatly enhances its adhesion to the anodize coating, and therefore endurance, although it does not increase its load-carrying capacity.

5. Performance/Applications

Performance properties must be taken into account in deciding what formulation to use for a specific application. For spacecraft lubrication systems, coefficient of friction, load-carrying capacity, electrical conductivity, temperature, and presence of liquid oxygen or radiation are conditions that must be considered. Environmental exposure during terrestrial testing and storage must also be considered, including resistance to degradation from oxygen, humidity, and other atmospheric gases.

General guidance as to the relative properties of different solid lubricant formulations is listed in Table 4. Information in this table can help to achieve a balance between competing performance characteristics. However, there are exceptions to these general guidelines. An example of over-generalizing solid lubricant performance is the average contact stress. The allowable average contact stress numbers listed in Table 4 are typical for many applications. However, they could vary by as much as a factor of 2, depending on the type of contact (sliding versus rolling) and the number of cycles required. In addition, contact stress may vary during different regimes of operation, so stresses could be considerably higher than the average much of the time.

These uncertainties suggest that selection of a lubricant system should only be accomplished in consultation with personnel at lubricant manufacturing companies and at manufacturers of space hardware, vendors, and bearings. There is also extensive industrial experience available in the literature [see, for example Reference 37]. In addition, testing (discussed below) should be done to simulate the varying stresses and other conditions seen in the actual space mechanism to evaluate if the lubricant is robust enough for use.

5.1 Unbonded Films

The easiest method of solid lubricant application is forming a lubricant film on a surface without mixing with a binder material. The lubricant is present in a powder form, and is applied to the part's surface by burnishing, spraying with an air blast gun, or mixing with a volatile solvent (which subsequently evaporates). As discussed in Section 4, the particles are held to the surface by relatively weak van der Waals forces, or they can be mechanically held in depressions on a roughened surface. In space applications, such films are usually formed from MoS_2, WS_2, or PTFE powders. Graphite is generally not recommended for spacecraft use, since it requires a partial pressure of water to operate effectively, as discussed in Section 7.

Although application of unbonded films is simple and inexpensive, the resultant film is poorly adherent. Also, unbonded films can exhibit poor reproducibility, with variations in film thickness and particle morphology. The film thickness of burnished films depends on several parameters that are difficult to control. For example, burnished MoS_2 films can be made 0.1-10 μm (4-400 μin.) thick, depending on rubbing time and burnishing method (e.g., cloth versus tissue). Also, the thickness can depend on the relative humidity during burnishing (38). However, even after controlling thickness through rigorous analysis of the effect of burnishing and humidity, after a short amount of device operation, all bets are off. Operation of the device will rapidly cause an unreproducible amount of MoS_2 to be removed from the contact region, leaving a film with unpredictable, though usually much smaller, thickness.

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Table 4. Design Guidelines for Solid Lubricants

Solid Film Lubricant Formulation[a]	Property												
	Maximum mean contact stress (ksi)[b]	Friction (dynamic)	Approximate thickness	Thickness variation	Minimum Temperature (°C)	Maximum Temperature (°C)	Adhesion	LOX compatible	Sliding/Rolling (S/R)[c]	Relative Endurance	High speeds[d]	Robustness to storage in high humidity	Resistance to condensed moisture
Unbonded MoS$_2$ or WS$_2$	200	0.02-0.1	0.1-10 μm	±80%	-260	900	Low	Yes	S / (R)	Very Low	Poor	Fair	Fair
Unbonded PTFE	10	0.02-0.2	1 μm	±80%	-35	150 to 250	Low	Yes	S / (R)	Low	Poor	Very good	Very good
Resin-bonded/ Heat Cured	100	0.03-0.1	10 μm	±50%	-220 to -70	200 to 400	Medium	No	S / (R)	High	Fair	Very good	Good
Resin-bonded/ Air Cured	50	0.03-0.1	10 μm	±50%	-220 to -70	150 to 400	Medium	No	S / (R)	Medium	Fair	Good	Fair
Inorganic-bonded/ Heat Cured	150	0.03-0.2	10 μm	±50%	-250 to -70	370 to 850	Medium	Yes	S / (R)	Low	Fair	Fair	Poor
Ceramic-bonded/ Heat Cured	100	0.1-0.2	10 μm	±50%	-240 to 20	600 to 1100	Medium	Yes	S / (R)	Medium	Fair	Fair	Poor
Sputter-Deposited MoS$_2$	150	0.003-0.05	1 μm	±10%	-260	400	High	Yes	S / R	High	Fair	Fair/Good[f]	Fair/Good[f]
Ion Plated Pb	130	0.1-0.3	0.1-1 μm	±10%	-260	300	High	Yes	(S) / R	Medium	Fair	Fair	Fair
Bulk Lubricating Materials[e]	1-50	0.02-0.4	~1 cm	N/A	Varies	Varies	N/A	Yes	S / R	High	Varies	Varies	Varies

a Formulations are often combined to optimize properties, e.g., using both sputter-deposited MoS$_2$ and a PTFE-containing cage in a ball bearing.
b Actual maximum mean dynamic stress will vary with, e.g., type of application, sliding/rolling speed, and expected lifetime, etc.
c Minor application is listed in parentheses ().
d High speed applications generally require liquid lubrication under hydrodynamic conditions
e Properties vary with specific material and application; e.g., PTFE journal bearings withstand only low stresses, but, PTFE-based bearing cages can be used in higher stress bearings since they indirectly transfer lubricating material to contact region.
f Improved by cosputtering with materials such as metals or PTFE, or by forming metal/MoS$_2$ multilayers.

Such variations and the poor adherence of unbonded films limit use to noncritical or undemanding applications. For example, burnished MoS_2 and PTFE are often used as antiseize lubricants during installation of screws, rivets, and connectors on space hardware. Attempts to use unbonded films as the sole lubricant in bearings, even for low numbers of cycles, have met with failure. Pressure-sprayed MoS_2 provides an increase in adhesion over simple burnished MoS_2 films, but it is still no substitute for bonded or sputter-deposited films in applications such as bearings, where there are higher stresses and greater sensitivity to debris.

However, burnished MoS_2 films can provide improved bearing performance when used in combination with other lubrication technologies. For example, bearings that use self-lubricating, MoS_2-containing cages will undergo a more graceful run-in, with lower initial wear, if MoS_2 powder is burnished onto the bearing races. Although sputter-deposited MoS_2 films have been demonstrated to perform this task successfully, sputter-deposition may be impractical if, for example, the bearing size is too large.

5.2 Bonded Films

Bonded film lubricants are widely used for many applications, but are best under low speed conditions such as gears, cams, sliding bearings, or other sliding elements in space mechanisms (39,40). The choice of the correct bonded film for the application requires taking into account the required friction level and operational lifetime, the application (e.g., sliding versus rolling), contact stress, the part material, the required part tolerances, as well as the composition and temperature of the operating environment.

Also, the type of substrate influences the allowable cure temperature and the type of surface pretreatment. The importance of appropriate substrate surface pretreatment was discussed in detail in Section 4, and is illustrated by the following two examples.

- Timken T54148 test rings were coated with phenolic resin-bonded MoS_2/graphite films (5). Samples were tested on the LFW-1 test apparatus (block sliding on ring) at 72 rpm (0.87 mm/sec) and 630 lb load. With no pretreatment, the film failed on loading. Two other samples underwent vapor degreasing followed by sandblasting, but the second one was subsequently treated to an additional phosphate treatment before coating. The first failed at 2×10^4 cycles, while the phosphate-treated surface lasted to 6.7×10^5 cycles.

- Journal bearing tests were conducted using phenolic resin-bonded MoS_2 films (39). Contact pressures were 3-4 ksi, with 0.87 mm/s sliding speed. In those tests, films deposited on 304 CRES exhibited wear lives 3-10 times greater than films deposited on 440C CRES. Both steels underwent the same pretreatment (grit-blasting followed by passivation). However, the 304 CRES surface was rougher, so that the adhesion of the lubricant film was greater.

The coefficients of friction for bonded films are generally in the range of 0.03 to 0.1 for a wide array of conditions (see Table 4). For a specific condition and contact stress, that range is much smaller, even for different types of films. For example, a comparison of performance properties for commercial bonded lubricant films was made using a Falex wear tester at 12 to 24 ksi (5,41). Coefficients of friction for all films fell in the range of 0.06 to 0.07 under these testing conditions.

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It should also be noted that claims have been made that the bonded film friction rises considerably at low temperatures. This may be related to testing conditions (i.e., nonvacuum), since the condensation of even a small amount of water on a film's surface could greatly increase friction. Although bonded films are not the optimum choice for cryogenic applications, manufacturer specification sheets often specify that inorganic-bonded films can operate (under the right conditions) down to -250°C, and organic-bonded films down to -220°C (see Table 4).

Bonded films are best used in applications that use sliding (as opposed to rolling) surfaces, low sliding speeds, moderate to high contact stresses, and large clearances. Because of the large thickness and thickness variability, bonded films are not appropriate for dimensionally critical applications (i.e., small clearances). In addition, significant amounts of debris can be produced during wear of bonded films (containing both binder and lubricant), so contamination- or debris-sensitive applications might perform poorly with bonded films.

An example of an appropriate application is the lubrication of gears for the Space Station Remote Manipulator System (SSRMS). Contact stresses are in the range of 25 to 100 ksi. Gears were tested with both organic- and inorganic-bonded MoS_2 coatings and a Pb-based coating (42). The organic-bonded MoS_2 coating showed no apparent wear over several million cycles, outperforming the inorganic-bonded MoS_2 coating, which showed some wear and failed after ~4 × 10^5 cycles. The bonded MoS_2 coatings both greatly outperformed the Pb-based coating which failed after ~2 × 10^4 cycles; considerable wear was seen on the gear teeth for the Pb-based coating.

5.2.1   Organic-Bonded Films

The most common bonded films for space applications contain MoS_2, along with various binders and additives. Historically, the commonly used lubricating pigments were 90% MoS_2/10% graphite, although the graphite provides no lubricating ability once in the vacuum of space, as discussed above. [There is a possibility that organic molecules from the binders could intercalate the graphite, helping to reduce friction, or that graphite could work synergistically with MoS_2 to reduce friction and prolong wear life (43).] The lubricants WS_2 and PTFE are also used, and small amounts of Ag, In, and Pb are occasionally added. The addition of Sb_2O_3 is thought to improve low-load properties of films (13) or to help in orienting the lubricating pigment within coatings (44), or both.

Organic-bonded solid-film lubricants generally use resins as binders, and can be either heat cured or air cured, depending on the application and the thermal stability of the part material. These lubricants can be applied by spraying, dipping, or brushing. Spraying is usually the best method, since it gives a more uniform film; however, spraying still requires careful process control to do correctly. Dipping produces films with the least uniformity.

A major factor in the choice of binder material is the cure temperature. The relative merits of heat-cured versus air-cured films are presented in Table 4. In general, heat-cured films withstand higher loads and exhibit greater endurance. They also tend to be more resistant to corrosion or attack by chemicals/solvents.

5.2.1.1 Heat-Cured Films

Heat-cured resin-bonded films are the most widely used solid lubricant formulations today. However, some types of heat-cured films cannot be used because the binder requires a cure temperature higher than that tolerated by the substrate. Undercuring (too low a temperature or too short a cure period) causes poor adhesion and fluid resistance. Overcuring causes reduced wear life due to oxidation of the binder, with resultant poor adhesion. Also, TMDs such as MoS_2 and WS_2 can oxidize if the films are cured too long, affecting friction. Specific cure temperatures appropriate for different lubricants and substrates are presented in Table 3 (including footnote c).

Besides cure temperature, different binders have different tribological properties, corrosion resistance, ease of application, and operating temperatures. The relative merits of thermosetting organic resins used in heat-cured films are presented in the following list:

- Phenolics: good surface adhesion, harder than alkyds and epoxies

- Polyimides: good in high-load applications.

- Epoxy resins: good solvent resistance, good adhesion, but softer than phenolics. (Modified epoxy-phenolics comprise properties of both materials.)

- Silicones: higher operating temperature than phenolics, but softer and only fair adhesion.

- Alkyds: Easy to handle, inexpensive, but softer than phenolics.

In many applications, phenolics provide the best trade-off between cure temperature and wear endurance.

5.2.1.2 Air-Cured Films

Air-cured organic-bonded films provide a happy medium in performance between unbonded/impinged films and heat-cured bonded films (45). Air-cured films provide enhanced lubricity/wear life and increased corrosion protection over unbonded films, although heat-cured films are more corrosion resistant. Binders used are generally thermoplastic resins, such as celluloses, acrylics, alkyds, epoxies, vinyls, and acetates. MoS_2 and PTFE are commonly used in air-cured films as lubricants for space applications.

An important limitation of air-cured films is that they do not generally meet outgassing requirements for space, as detailed in the ASTM test method E595-90 (46). Since this test requires heating the sample to 125°C, air-cured films usually cannot be used on space hardware without a waiver. Since many heat-cured films can be cured by heating to a temperature only slightly higher than for the test (i.e., 150°C), they are preferred for space applications. In general, a lubrication formulation other than bonded films may be appropriate for heat-sensitive materials used in space hardware.

5.2.2 Inorganic-Bonded Films (Nonceramic)

The main inorganic binders used for space applications are silicates (e.g., Na_2SiO_3) and phosphates (e.g., $AlPO_4$), although aluminates, organometallics, and other compounds have been used. Inorganics replace organics as binders for applications requiring liquid oxygen compatibility. They can also tolerate moderately elevated temperatures (some inorganics can be used up to 850°C), which is unimportant for space applications except for some propulsion systems [e.g., low cycle bearings on launch vehicles (37)]. In addition, because they are harder than organics, inorganic binders can tolerate greater loads (i.e., ~150 ksi versus ~100 ksi for organics) (3). However, because they are more brittle and wear more easily, inorganics can only be used in applications where lower movement (i.e., less cycles) is required. Examples include various types of gears and low cycle bearings (37). Other limitations involve their tendency to soften in the presence of water/humidity, and (for some) their poor corrosion resistance. The main lubricant mixture used with inorganic-bonded films is, again, 90% MoS_2/10% graphite. Other materials such as PbS and various metals are sometimes added.

5.2.3 Ceramic-Bonded Films

Ceramics are used as binders for high-temperature applications (i.e., up to 1100°C), where resin-bonded and even inorganic-bonded formulations will not work. Since such temperatures are higher than those usually required for space-based applications, these films will be discussed only briefly here. They are discussed in more detail in References 5 and 47.

TMDs such as MoS_2 and $NbSe_2$ cannot withstand temperatures higher than 400-500°C, so other lubricants are used, including usually Group IIA fluorides such as CaF_2, MgF_2, or CaF_2/BaF_2 eutectic mixtures. PbO can also be used. Aluminum phosphate is often added for strength. Although there are exceptions, resin-bonded films outperform ceramic-bonded films at lower temperatures. Also, most ceramic-bonded films require curing at temperatures above 500°C, so only refractory metals and alloys, or other refractory materials, can be used.

5.3 Sputter-Deposited Films

MoS_2 is the most common sputter-deposited lubricant. Its film properties are critically dependent on adhesion, microstructure, and composition (33,48). Adhesion can be optimized by appropriate surface treatment (discussed below). Also, the deposition process itself encourages good adhesion, since the plasma promotes intermixing between the substrate and the deposited film. The important microstructure variations relate to film density, since more dense film morphologies can result in decreased friction and increased endurance. However, without the addition of other chemical species during film growth, the resultant smaller crystallite sizes can result in poorer oxidation resistance that can occur during extensive terrestrial storage. Dense films with small crystallite size are favored by factors that inhibit grain growth, including low substrate temperature, dopants that inhibit adsorbed atom mobility, lower growth pressures, or ion bombardment during growth (i.e., IBAD).

The composition of the film is the third critical parameter, and encompasses both the intentional and unintentional addition of species. Unintentional introduction of additional species in sputter-deposited MoS_2 films usually takes the form of oxygen incorporated during sputter-deposition and

after exposure to atmosphere. Because the Mo-O bond is stronger than the Mo-S bond, the presence of relatively small amounts of water vapor in the chamber during deposition (as low as 10^{-6}-10^{-5} Torr) can result in appreciable amounts of oxygen being incorporated in the films (49-52). Generally, films contain 5%-15% oxygen. If the water vapor pressure is not too high, a mixture of poorly crystalline MoS_2 and $MoS_{2-x}O_x$ phases results in the films. The $MoS_{2-x}O_x$ phase (where x is continuously variable) has an MoS_2-like structure, with oxygen atoms substituted for sulfur atoms in the MoS_2 crystal lattice. Because of the sulfur depletion, previous studies have assumed that films were present in a MoS_x-type composition, but these studies did not adequately account for the presence of oxygen in the films. All sputter-deposited films in production today contain appreciable amounts of this phase; even if they are deposited in a highly pure sputtering ambient, the films absorb some oxygen-containing species to produce the $MoS_{2-x}O_x$ phase after brief exposure to atmosphere (17). The presence of this oxygen-containing phase is not detrimental, but should be understood and controlled during film growth since varying oxygen contents can affect the microstructure and friction coefficient in the films. In fact, friction may decrease with increasing values of x in $MoS_{2-x}O_x$ (51-53). However, a sufficiently high water component in the sputtering ambient could lead to MoO_3 formation, which would be detrimental to both friction and wear life. The detrimental formation of MoO_3 can also occur during prelaunch storage; this is discussed in Section 7.

MoS_2 can be intentionally cosputtered with a metal or other compounds. Cosputtered films can be deposited from single composite targets or from two separate targets used simultaneously. These materials have been shown to exhibit desirable tribological characteristics, including enhanced wear life as well as lower and more stable friction (54-57). Metals can densify the films by poisoning the edge of the MoS_2 crystallites during growth of the films (48,58,59) (see Fig. 3a and 3b). They can also reduce the oxidation of the MoS_2 crystallites themselves by acting as sacrificial oxidants, and by "sealing" the reactive edges of the crystallites (59).

A promising method of using metals to control film morphology is to form multilayer films, or heterostructures, consisting of alternating layers of MoS_2 and selected metals. Beneficial results have been obtained with metals such as Ni or Au(Pd) alloy (56,59,60), and other metals such as Mo are being explored. The resultant multilayer film structures are dense, which can enhance wear life (see Fig. 3c). In addition, the MoS_2 layers tend to grow with their basal planes parallel to the substrate, reducing fracture of the crystallites during wear. Recent results show that the fracture toughness is improved for decreasing layer thicknesses and for increasing amounts of metal in the films (61). This enhanced toughness is especially important for rolling applications. In sliding applications with lower stresses, lower metal contents appear to be desirable. Multilayer films are grown using sequential deposition from two separate targets.

It was once thought that sputter-deposited MoS_2 films would always be the "lubricant of the future," but they are being used increasingly to lubricate components in new programs, such as on the European Space Agency's (ESA's) Infrared Space Observatory (ISO) (14,62) ENVISAT-1 (63), TRIAD (37), and many new NASA (64) and military space vehicles in the U.S. The friction coefficient of most sputter-deposited MoS_2 films is considerably lower than for most other solid lubricant formulations. The resultant decrease in torque of the lubricated device is attractive, considering the need to reduce power budgets on spacecraft. Also, sputter-deposited films are good choices for dimension-critical applications, since their thickness and thickness variability are small relative to other formulations (see Table 4). Although pure sputter-deposited MoS_2 films may exhibit more moisture sensitivity than resin-bonded films, the newer film structures containing added metals and other compounds exhibit greater robustness with respect to

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(a)

2 μm
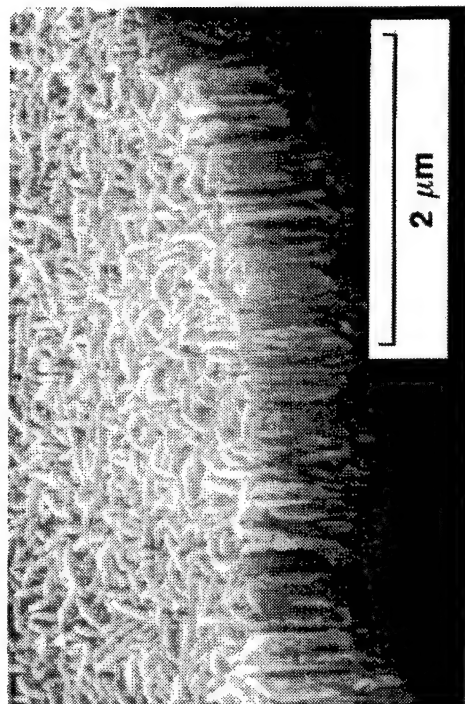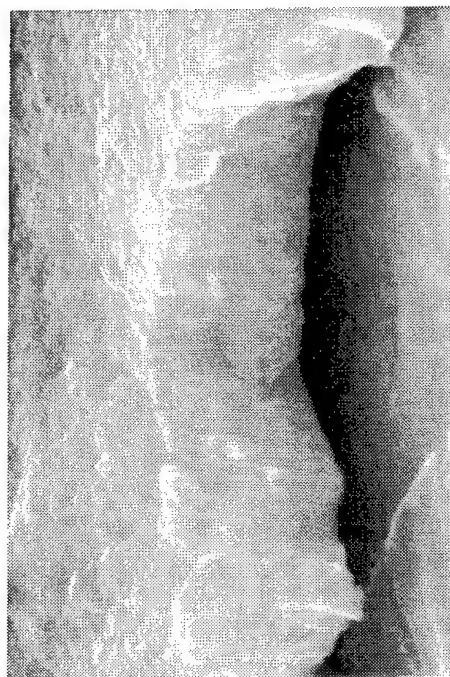
(b)
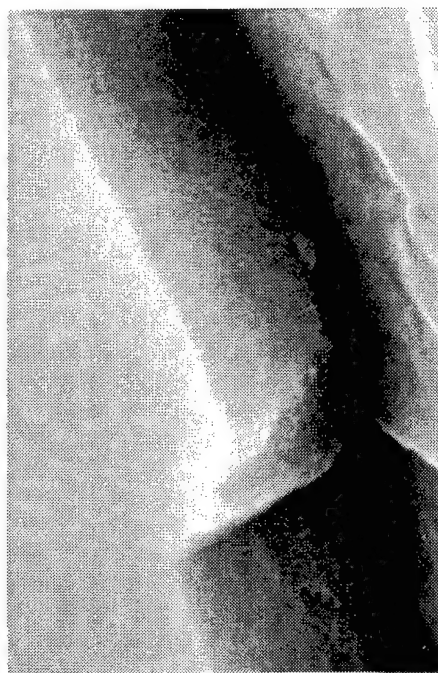
(c)

Figure 3. Photographs of cross sections of sputter-deposited MoS$_2$ films, showing the effect of film doping on structure. The cross sections are produced by fracturing the films using a Rockwell indenter. Shown are (a) pure rf-sputtered MoS$_2$, (b) DC-sputtered MoS$_2$ cosputtered with Ni, and (c) rf-magnetron-sputtered multilayers consisting of alternating layers of MoS$_2$ and Ni.

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humidity. A main drawback to usage of these films is the difficulty in coating large parts. Some also see the cost as prohibitive, although a few extra thousand dollars is not excessive if it provides additional confidence for a mission that costs tens or hundreds of millions of dollars.

5.4   Metal Films

Thin metal film lubrication is useful mainly for rolling rather than sliding applications (11,34,65). Typical thickness of the films falls in the range of 0.1 to 1 μm, which corresponds to both maximum wear life and minimum coefficient of friction (11,34). Films can be deposited by electroplating, evaporation, sputter-deposition, and ion-plating. Sputter-deposition and ion-plating (25) give films with good adhesion, while allowing control over film thickness and uniformity. In addition, the compositions and morphologies are more controlled than they are for the electroplating process. Ion-plated lead films have proven especially useful for rolling element bearings involving relatively slow rates of rotation in space mechanisms (e.g., solar array drives) (14,65).

Besides Pb, the noble metals Ag and Au have been used. For example, an Au(Co) alloy coating is planned for lubricating ring tracks and rolling flexures in the roll ring assembly on Space Station Freedom (66). Also, Ag films have been explored as a solid lubricant for ceramic coatings (i.e., Si_3N_4 and ZrO_2) (67). When tested in pin-on-flat contact with a light mineral oil at ~150 ksi hertzian stress, the Ag films exhibited coefficients of friction 2-3 times lower than for uncoated ceramic surfaces, and reduced wear rates to negligible levels.

5.5   Ion-Implantation

Part of the reason N-implantation lowers the wear of steels is that it enhances hardness, which is believed to be due to the formation of hard metal nitrides (68). Another possible reason is the presence of an amorphous layer produced by implantation; such a layer would inhibit crack propagation, increasing fatigue strength. In many cases, ion-implantation also reduces friction. However, even in cases when friction remains the same or even increases, improvements in wear rate have been seen. Studies have been done to investigate the specific effects of ion implantation on a number of steels and other materials. There are an almost infinite number of parameters to vary in determining the optimum tribological properties of a specific implanted material, including the type, energy, and fluence of the implanted species. Results of some of these studies (69-77) are shown in Table 5.

5.6   Composite Materials

As noted in Section 3, self-lubricating materials are primarily used in space mechanisms as cage materials in ball bearings, and as bushings. Under the right circumstances, composite materials provide low friction, but they usually cannot be used in applications where they are under high contact stress: the structural materials used (e.g., polymers, brass, glass fibers) provide strength, but not hardness. A rule of thumb is that they can be used with line or point contacts only when the load is low (i.e., less than about 1 ksi); they work best with area contact.

Although not composites, some monolithic polymer materials are included in this category because they are also used for bearing cages and bushings. These polymers are designed to provide a

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Table 5. Examples of Tribological Studies of Ion-Implanted Surfaces				
Substrate	**Implant-ing Atom**	**Fluence (ions/cm^2)**	**Torque/ Friction Decrease**	**Wear Decrease**
440C bearings (balls and both races implanted) (69)	N	4×10^{17}	1.7 ×	25 ×
440C ball-on-plate (plate implanted) (70)	B	10^{16} to 10^{17}	4 ×	NS [a]
440C pin on: 440C disk 304 SS disk (disks implanted) (71)	Ti+C "	NS 2×10^{17}	2 × 2.3 ×	8 × 5 ×
52100 ball-on-plate (plate implanted) (72)	Ti+C	10^{17}	2-3 ×	NS
Ruby ball on: 304 SS disk 52100 steel disk 12T steel disk Ti6Al4V disk Iron disk Hard Cr plated disk (disks implanted) (73)	N	3.5×10^{15}	1.1 × NS NS 3 × 0.8 × 1 ×	30 × 0.8 × 5 × 500 × 2 × 50 ×
Ruby ball on Tool steel plate (plate implanted) (74)	N	NS	2 ×	NS
Fe-Cr alloys (75)	B,N	2.5×10^{16}	2-4 ×	NS
Ti6Al4V pin-on-disk (both implanted) (76)	N+O	10^{17}	NS	4 ×
TiC pins on Si_3N_4 disks (Si_3N_4 implanted) (77)	Ti, Ni	NS	5 ×	NS

[a] NS = Not specified

balance between strength and low friction, and include polyimide, poly(amide-imide), and poly(aryletherketone) (PEEK), as well as pure PTFE.

In bushings and sleeve/journal bearings, the contact is over a large surface area and contact stress is relatively low. In such direct contact applications, some transfer of lubricating material may take place, but lubrication is accomplished mainly by providing a low friction interface between the (composite or polymer) sleeve and the (steel or other metal) rod.

Composite bearing cages provide low friction at the ball/cage interface, where contact stress is low. In addition, they provide low friction/wear at the high contact stress ball/race interface by lubricant transfer, first from the cage to the ball, and then from the ball to the race (11) (see Fig. 4). Transfer is inefficient, so a high percentage (>20%) of lubricant in the composites is necessary. As such, poor mechanical strength results in higher wear rates. Incorporation of PTFE facilitates transfer film formation, although in some cases large particles (lumps) of material can be transferred, causing noisy operation.

For polymers, wear rates in the early stages of sliding vary with roughness as $(R_a)^n$, where $n=2-4$ (11). Therefore, smooth counterfaces are recommended for dry bearings. However, the wear rate rapidly drops as the result of transfer of polymer and/or filler(s) caused by the polishing action of the filler. For polymer composites that contain solid lubricants, wear behavior is highly dependent on initial transfer films, which in turn are dependent on environmental factors. Relative humidity can either increase or decrease wear, depending on the type of filler. Therefore, to avoid processing variations and performance uncertainty, bearings to be used on spacecraft should be run in (worn) under a controlled environment (preferably vacuum or dry N_2). To aid in design, approximation schemes exist for predicting wear rates for a particular application (11),(78). Such schemes take into account the specific wear rate of the material (i.e., in m^2/N), and include factors for geometry (continuous versus oscillatory, movement of load on bearing), heat dissipation, operating temperature, counterface material, and counterface roughness.

There is considerable evidence that the use of thin lubricant films on the races (and sometimes balls) along with composite cages considerably improves performance and endurance, as opposed to using either the composite or the film alone. The film allows a graceful wear-in process, providing initial lubrication while the transfer film from the cage is being developed. Examples include Pb/bronze cages with ion-plated Pb films deposited on the bearing races (79), and PTFE-based cages (glass or bronze as a filler) with sputter-deposited MoS_2 films on the bearing races (80-82).

Many instances of the use of composite materials for bearing cages can be found in the published literature. Some specific examples are provided here to give the reader some appreciation of the versatility of this type of design. Bronze- (Salox-M®) or glass-fiber (Rulon A®)-reinforced PTFE with MoS_2 added showed the lowest wear in bearings for Pratt & Whitney's RL-10 H_2/O_2 engine (83). PTFE or polyimide cages with MoS_2 coatings on the races, or Pb bronze cages with Pb on the races, were tested for oscillating (gimbal type) bearings. Different levels of performance were obtained depending on the oscillation arc (84). Pb systems were better for small arcs, $\pm 0.5°$, while MoS_2 was better for $\pm 5°$ and $\pm 20°$ oscillations. A more detailed study of polyimide cages, including fluorinated material, showed that a formulation with 7.5 vol% MoS_2 and fluorinated polymer gave the best overall performance: longest life with lowest friction noise (85).

In another study, angular contact bearings were tested in vacuum from 300 K down to 20 K (79). Three lubricating systems were used: (1) PTFE transfer films from a Duroid (glass-filled

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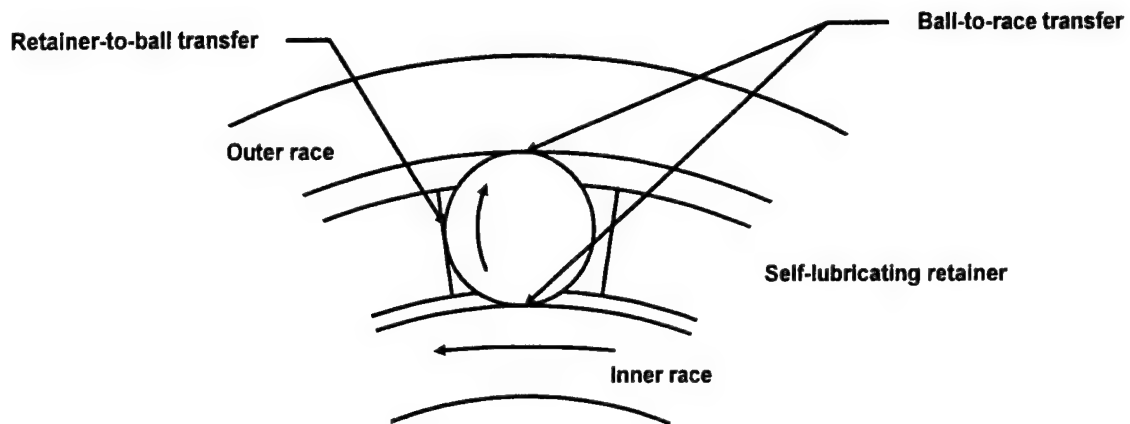
Figure 4.   Cross-sectional schematic representation of a self-lubricating bearing. Lubrication occurs via transfer of lubricant, first from the cage to the balls, and then from the balls to the races. The cage may be composed of a monolithic lubricating material, such as polyimide or PTFE, or more commonly of a composite mixture of one or more lubricants (e.g., MoS_2 or PTFE) with a stronger material for structural integrity (e.g., glass fibers, bronze, or polyimide).

PTFE/MoS$_2$) cage, (2) ion-plated Pb films on the races with a Pb-impregnated bronze cage, and (3) sputter-deposited MoS$_2$ on the races with several cages (Duroid, MoS$_2$-coated steel, and MoS$_2$/polyimide composite). Pb-coated bearings were noisier than Duroid (with or without sputter-deposited MoS$_2$), but the Pb-coated bearings showed no torque deterioration on reducing the temperature from 300 K to 20 K, while the Duroid bearings all showed some minor deterioration. All of the bearings tested at 20 K survived at least 2 million revolutions. Additional low-temperature data (14) show that using sputter-deposited MoS$_2$ as the only lubricant deposited on the races, balls, and the steel cage was the best performer of all (although only mean torque values were shown; no noise levels).

Thin metal films can also be applied as composites. For example, the interiors of telescopic tubes used in a deployable/retractable telescoping boom were coated with a PTFE-impregnated electroless Ni plating (86). The Ni/PTFE coating lowered friction and prevented galling between the Al in the tubes and the tips of latch pins during deployment.

Another similar process is to impregnate PTFE into porous surfaces such as anodized Al coatings. The low friction of PTFE and the small thickness of these films is attractive, but care must be taken to use them only in low contact stress applications. Although such films are thought of as composite films, the porosity of the oxide is sometimes difficult to control, so the PTFE may be present only on the surface of the anodize layer. In such a case, the process can only be used for contact stresses 1-10 ksi, since above this level the PTFE will cold flow, and galling of the anodize and underlying Al can result.

6. Friction and Wear Testing

There are two categories of testing pertinent to solid lubricated devices, both which are critical to understand for the spacecraft mechanism designer. The first category includes tests that are standardized for use with solid lubricants. As discussed below, standard tests provide a common language for comparing lubricants produced by different manufacturers, and provide qualitative guidance in film selection criteria for the mechanism designer. However, they usually cannot provide quantitative friction/torque, wear rate, or endurance life values for a specific application. As such, any lubricated device must be subjected to the second category of testing, which duplicates the conditions of the actual device as closely as possible.

6.1 Standard Tests for Solid Lubricants

Standard performance testing of solid lubricant systems is important for the lubricant manufacturer during development of new lubricating materials, for quality control during lubricant manufacture, and for providing quantitative criteria for manufacturing specifications (e.g., Milspecs and NASA specifications). Examples of wear tests are listed in Table 6. These tests are discussed in more detail in References 4, 11, 29, and 30.

For mechanism design engineers (i.e., users), compiling manufacturers' standard test results for a number of lubricant formulations can aid in the selection of the best lubricant for their application. However, such data can at best only narrow the field to a specific class of lubricants. To decide on the optimum lubricant formulation for a specific application, more custom-designed testing is required; this is discussed in more detail below. However, after choosing the optimum lubricant, such standard tests can also be useful for quality control. This is especially important during a long space program, where satellites or launch vehicles are built over a period of years, where lubricant formulations and film application procedures might undergo change. For bonded or other solid lubricant films, the end user should request that standard test blocks be coated along with the actual flight parts. Testing of each lubricant batch will ensure that the manufacturing quality remains constant throughout the life of the program.

Care must be taken to understand the conditions under which the tests shown in Table 6 are conducted. For example, the environmental conditions are often different from the intended application: tests may be conducted in air or nitrogen and the application in space is usually $<10^{-6}$ Torr vacuum. Also, the wear life of thin solid film lubricants is usually characterized by determining the amount of time or sliding distance for the coefficient of friction to rise to some arbitrary value, usually about 0.3. Such a value could be considerably higher than would be allowed in a specific application, so that the test could overestimate the endurance. Also, even in carefully controlled conditions, there can be significant scatter in the results. Therefore, it should be emphasized that a number of tests should be performed for a single set of variables to characterize the level of error in the results. With the Timken apparatus, scatter can exceed ±100%, while with the Falex test, scatter tends to be less than ±50% (11).

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Table 6. Standard Tests for Solid Lubricating Systems [see also Refs. (4) and (11)]				
Test Name	Type of Test	Type of Contact	Type of Motion	1) What is Measured 2) Typical Applications
Shell 4-ball	Four 0.5"-diam. balls	Point	Continuous sliding	1) CF [b], max. load, wear 2) Solid dispersions in oils
Reichert	Crossed cylinders (Pin on ring)	Point	Continuous sliding	1) CF, wear 2) Solid dispersions in oils, thin films
–	Pin on disk	Point	Continuous sliding	1) CF, wear 2) Thin films, self-lubricating composites
Timken [a]	Block on 1.94 in.-OD ring	Line	Continuous or reciprocating sliding	1) CF, max. load, wear 2) Thin films, self-lubricating composites
Alpha LFW1 [a]	Block on 1.375 in.-OD ring	Line	Continuous or reciprocating sliding	1) CF, max. load, endurance, wear 2) Thin films, self-lubricating composites, solid dispersions
–	Pad on ring	Line	Reciprocating	1) CF, max. load, endurance, wear 2) Thin films, self-lubricating composites; bearing liner materials
Falex [a,b]	Pin in V-blocks	Multiple line	Continuous sliding	1) CF, max. load, endurance, wear 2) Thin films, solid dispersions
Hohman A-6 [a]	Two blocks on 1.94 in.-OD ring	Multiple line or conforming	Continuous sliding	1) CF, max. load, endurance, wear 2) Thin films, self-lubricating composites; bearing liner materials
Almen-Wieland	Journal bearing (0.25 in.-OD pin in shells)	Conforming	Continuous sliding	1) CF, endurance, wear 2) Thin films, self-lubricating composites; simulate bearing applications
Alpha LFW3	Thrust bearing (annular ring on block)	Conforming	Continuous or reciprocating sliding	1) CF, endurance, wear 2) Thin films, self-lubricating composites; simulate bearing applications
Alpha LFW4	Press-fit (pin in bushing)	Conforming	Axial insertion	1) CF 2) Burnished/rubbed powders, thin films, solid dispersions

[a] Most common tests
[b] Required test for bonded film specifications MIL-L-46010B, MIL-L-46147A, MIL-L-23398D
[c] CF = Coefficient of friction

6.2 Testing of Solid Lubricants for Actual Application

Any amount of standard testing is no substitute for conducting tests of the lubricant on parts that are identical to those that will eventually be used in flight hardware. All conditions should be as close as possible to those experienced in flight. Specific areas of concern are:

- Lubricant
    - Formulation
    - Surface preparation
    - Film application method (e.g., thickness)
    - Part dimensions
    - Part tolerances
    - Load/contact stress - static and operating
    - Sliding versus rolling (e.g., sliding-to-rolling ratio of ball in bearing)
    - Motion
        - Continuous
        - Reciprocating
            - Square wave, sine wave, or sawtooth
            - Length of wear path: e.g., when dithering a ball bearing, is there ball-to-ball overlap?
        - Two-dimensional movement; e.g., antenna pivot point undergoes complex x-y path that is difficult to model during testing
    - Speeds
    - Launch vibration levels
    - Temperature
    - Gas and impurity environment
        - Usually vacuum for space hardware
        - Outgassed contamination from other spacecraft devices

Setting the test requirements is critical in the design process of the lubricated mechanism. Qualification tests are conducted on the spacecraft mechanism to show robustness of the design, by carefully choosing a set of operating conditions that are more stressful than expected to be seen on-orbit. Generally a life test is included, where the device must show nominal performance over a specific number of expected lifetimes (often two). Functional testing is usually conducted before and after the life test, and sometimes during the test. Such functionalities may include measurement of torque, torque noise, degree of wear (e.g., for maintaining tolerances), pointing accuracy, and/or performance of devices/subsystems mounted on the moving mechanical assembly. Testing for load margin can be problematic, since solid lubricants tend to have good life margins and narrow load margins. Overloading a lubricated device could cause immediate failure of the device; providing justification for the design at this point can become costly.

The qualification test plan also usually includes thermal cycling, either as part of the life test or as a separate test. The temperature excursions are usually larger than those expected on-orbit. Vibration testing is performed (mainly) to simulate the vibration seen during launch, and is usually done separately from the life test.

Acceptance testing is usually performed at several levels: first at the component level, then at the subsystem level, and finally at the system level (i.e., the complete satellite or launch vehicle). The component level test is sometimes deleted, which can be a mistake. If a problem with the lubricant is seen at the component level, subsequent rebuild can be loss costly than at the subsystem or system stages. The acceptance test may involve operating the device over some fraction of its

intended life on orbit. In addition, thermal cycling and variation of other parameters may be conducted. Such variations are generally more than those seen on orbit to verify robustness, but less than for the qualification tests to avoid impairing the ultimate effectiveness of the device.

7. Cautions

Although solid lubricants solve a number of tribological problems in applications where liquids are not appropriate, their limitations must be considered when designing the lubricated device, and when determining proper test and storage procedures.

7.1 Humidity Sensitivity of MoS₂

MoS_2, the most common solid lubricant for space, is chemically unreactive with respect to most solid and liquid materials. However, its tribological properties may degrade when exposed to humid air, either during testing (4,87) or storage (88,89). The mechanism of degradation involves chemical reaction of the MoS_2 with the water vapor and oxygen in the air (11,88). Two reactions can result:

$$2MoS_2 + 4H_2O + O_2 \rightarrow 2MoO_3 + 4H_2S \tag{1}$$

$$2MoS_2 + 4H_2O + 9O_2 \rightarrow 2MoO_3 + 4H_2SO_4 \tag{2}$$
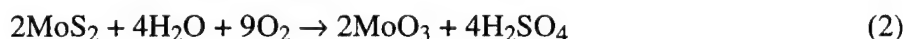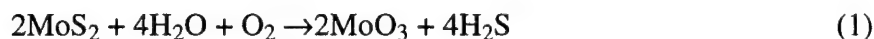
Both reactions entail MoS_2 reacting with H_2O and O_2 to produce MoO_3, which is not a good lubricating material. [MoO_3 had been characterized as being abrasive besides being nonlubricating, but this was shown not to be the case (90).] In addition to converting the MoS_2 to a nonlubricating form, in reaction (1), the gas H_2S is produced. Although H_2S does not directly affect tribological properties, it can react with silver in MoS_2-lubricated electrical contact ring assemblies to produce silver sulfide (Ag_2S), causing electrical noise during operation (88). The production of the acid H_2SO_4 has caused the establishment of pH limits of aqueous extracts of MoS_2 powders in several specifications (11).

Organic-bonded (generally resin-bonded) MoS_2 films are the most resistant to oxidation, since the reactive edges of the MoS_2 particles in the film are covered by the nonporous resin binder, and the resin itself does not absorb appreciable amounts of H_2O. The heat-cured films are more resistant to moisture incursion, and also to corrosion in general, than are the air-cured films. Polyimide-bonded MoS_2 films are exceptions, since the friction of polyimide increases as it absorbs moisture (12).

Inorganic-bonded MoS_2 films exhibit moisture sensitivity, especially when they come in contact with condensed water vapor. The binder, generally a silicate or phosphate, can absorb moisture, weakening the cohesion of the film. Although inorganic-bonded films are preferred for LOX applications (see below), their moisture sensitivity can preclude their use in other cryogenic applications. If the inorganic-bonded film is exposed to air during a cooling cycle, such as on a propellant fill valve for a launch vehicle, water vapor from the air can form a frost on the lubricant film surface. On detanking, the lubricated device warms to ambient temperature, the frost melts, and the resultant liquid water can destroy the integrity of the lubricant, especially during multiple tanking/detanking cycles.

Burnished MoS_2 films are formed from MoS_2 powders, and the films are somewhat porous, so they exhibit moisture sensitivity greater than that for bonded films. For example, the sliding wear lives of burnished MoS_2 films riding on steel were tested in various atmospheres. Wear lives for

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moist air, dry air, and dry argon were in a ratio of about 1:15:150 (91). However, burnished MoS_2 films are most often used during spacecraft fabrication as an antiseize lubricant for screws and rivets, so their degradation would not impair spacecraft performance.

Sputter-deposited MoS_2 films are potentially more susceptible to humidity-induced degradation, since they have smaller crystallite sizes and greater crystal defect levels than MoS_2 in burnished or bonded films. Surface chemical studies were conducted of the storage robustness of sputter-deposited MoS_2 films in humid atmospheres [i.e., 52% and 84% relative humidity (RH) (92)]. The surfaces of films stored in humid atmospheres showed approximately 50% greater oxidation than in dry atmospheres for storage times of 1 to 2 years (92). However, newer film growth techniques involving codeposition of MoS_2 with metals and MoS_2/metal multilayer formation show promise of producing films with greater humid storage robustness and improved tribological properties. Such robustness is due to lower film porosity and to passivation of the surfaces of the MoS_2 crystallites by the metals (56,60).

Studies at The Aerospace Corporation have been conducted on the effect of extended storage of MoS_2 powders in air with varying relative humidities (88). The results showed that for MoS_2 samples stored from 1 to 3 years, the rate of oxidation to MoO_3 was three times faster at 53% RH compared to 33% RH. In addition, samples stored at 4% RH exhibited about the same amount of oxidation as those stored at 33% RH. As such, considerable gains in lubricant stability can be obtained by reducing the maximum humidity requirement for spacecraft storage from 50% to 60% RH, which is commonly specified, to 30%. Although there is not much difference in the oxidation rate in air between 4% and 33% RH, additional reduction in oxidation rate could be achieved by storing the samples in dry N_2 gas, which excludes oxygen as well as water vapor. (The use of N_2 gas must be balanced against concerns related to electrostatic discharge, which may be problematic for relative humidities below 20%.)

7.2 Qualification by Similarity/Requirement Creep

Costly failures can occur during advanced stages of manufacture and testing of lubricated parts due to unwitting errors made in the qualification process. Often an application is "not too different" from one conducted previously, so that qualification tests are deemed unnecessary: the part/device is qualified based on similarity to the previous tests/application. Great care must be taken when "qualifying by similarity"; anomalies have occurred during acceptance testing or even on-orbit after overestimating differences in design between two applications.

An example of qualification by similarity might be bearings with self-lubricating retainers used in two different programs under almost identical conditions. The bearings might have the same design, use the same preload, and have similar speeds during operation. However, seemingly insignificant differences such as level of vibration during launch, reversing motion at regular intervals during operation, or a longer storage period before launch, could create enough performance differences that qualification by similarity is not justified.

Another pitfall can occur when seemingly small changes are made in the design or requirements of a lubricated device after qualification. Similarly, design changes are often made in the middle of a multisystem program. Such "requirement creep" often results in waivers being written to exempt a design or requirement change based on cost. However, such changes may cause anomalous performance. These problems are more costly to correct than the original redesign because extensive failure analysis must often be performed, and because of changes in inflexible delivery

and launch schedules. For example, relatively small changes in load can adversely affect performance because, as discussed earlier, solid lubricant films tend to have wide life margins, but narrow load margins.

7.3   LOX Compatibility

Organic resin-bonded lubricants are not LOX-compatible because impact of an organic solid in the presence of LOX can cause an explosion. In general, inorganic-bonded films are used. However, care must be taken to avoid contact between inorganic-bonded films and air when they are used below ambient temperatures, or water condensation can impair their integrity, as discussed above. The compatibility of materials with LOX is detailed in Reference 93.

7.4   Graphite

In order to lubricate effectively, graphite requires a partial pressure of water. The water is absorbed between the graphite crystal planes, allowing sliding to take place. As such, graphite is an excellent lubricant for use at elevations near sea level, but loses its lubricating ability at high altitudes and in the vacuum of space (4,11,94,95). Reference 95 showed that a partial pressure of water greater than 3 Torr is necessary to reduce the wear rate of graphite to negligible values. Air has 5-10 Torr water at typical humidities, but the partial pressure of water in space is $<10^{-6}$ Torr. Therefore, graphite in lubricant mixtures only allows lubrication during terrestrial testing in air (even dry nitrogen would impair graphite performance). As a result, most military specifications for bonded films require that graphite not be used as a lubricating pigment (29,30).

7.5   Thermal Conductivity

For lubricated devices that undergo large temperature excursions during operation, the thermal expansion of cured coating must be matched with the base material. If they are too different, the coating can fracture and separate from the substrate (13).

7.6   Atomic Oxygen Exposure

Nearly all materials used in tribological applications will degrade when subjected to atomic oxygen exposure in low earth orbit (34). Only sealed areas would be immune from degradation, since even shielded surfaces may be exposed to scattered atomic oxygen. One study (96) showed that exposing sputter-deposited MoS_2, inorganic-bonded MoS_2, organic-bonded MoS_2, and ion-plated Pb films to atomic oxygen beams gave 20%-30% increases in initial friction coefficients, although friction was the same for irradiated and nonirradiated samples within 2 min after the start of the test. Oxidation depths were 6 nm (0.24 μin.) for sputter-deposited MoS_2 films and 70 nm (2.8 μin) for inorganic-bonded MoS_2.

7.7 Materials Compatibility

Organic-bonded films, especially those with phenolic binders, should not generally be used in contact with oils/greases (3,4). Like organic solvents, they can soften the binder. Similarly, sputter-deposited and ion-plated films can be lifted off substrates by the intrusion of oils through defects or grain boundaries in the films, resulting in peeling and flaking of the films.

7.8 Tolerance Budgets

Unlike liquid lubricants, solid lubricants exhibit nonnegligible thickness, which should be subtracted from part dimensions when designing bearings and other lubricated devices. Also, manufacturers of bonded lubricant films often cannot specify lubricant film thickness to better than ± 0.2 mil (± 5 μm), which should be allowed for in calculating tolerance error budgets.

Design error budgets should also allow for the effect of wear. Even if a lubricant film thickness is well-characterized, there will be some reduction in thickness over the life of the part, much of which occurs during the early life (e.g., run-in). If wear measurement cannot be made during testing, a posttest surface analysis should be conducted.

7.9 Wear Debris

Small amounts of wear will naturally occur for solid lubricant formulations, especially early in life. The resultant wear debris must be allowed for when designing spacecraft mechanisms, especially with hard (preloaded) components. Determination should be made of the effect of debris on the performance of the device, as well as potential contamination effects on nearby devices, such as optical sensors.

8. Future Directions

Development of novel tribological systems for spacecraft mechanisms is concentrating primarily on improving the fabrication and deposition of existing materials, including TMDs (MoS_2, WS_2, and $NbSe_2$) and polymers. For example, there are several new deposition processes that are being used to make MoS_2 films with enhanced tribological properties and environmental robustness. These processes produce films with lower friction coefficients, greater purity, and control over film morphology/crystallinity. Only empirical testing will show whether their overall tribological properties are good enough to replace more traditional bonded and sputter-deposited MoS_2 films.

Although sputter-deposited MoS_2 films have been around for over 25 years (8), advances are still occurring that result in improved lubricating/antiwear performance. For example, "super-lubricating" MoS_2 films have been produced with friction coefficients of $\sim 10^{-3}$ rather than in the typical $\sim 10^{-2}$ range (18). The lower friction is thought to be related to higher film purity and the small crystallite size. Resultant lower defect levels may cause reduction in shear strength, producing the theoretical minimum in friction. However, exposure to air, which all lubricated mechanisms must undergo before use, resulted in absorption of oxygen into the films (17), which could cause the films to revert to typical film behavior.

A variation on conventional sputter-deposited MoS_2 is IBAD MoS_2 films. Because IBAD utilizes an ion acceleration source (i.e., ion gun), rather than an rf or DC plasma, to bombard the target, films can be produced with high purity (97). Control over the crystalline order and orientation can be achieved by varying the ion current bombarding the substrate surface during film growth, as well as other parameters. Also, the addition of metals like Pb during IBAD MoS_2 film growth can significantly increase endurance while maintaining low friction (98).

Another deposition technique involves electrophoretic deposition of MoS_2 (99). Films show good friction and wear characteristics in pin-on-disk tests, similar to those for sputter-deposited films. The attraction of a wet chemical process is that it is much simpler than physical deposition, and parts with unusual geometries can be coated.

Few new materials show promise of surpassing MoS_2 and PTFE in solid lubricating ability. However, one possible new material is formed by the fluorination of graphite to produce substoichiometric graphite fluoride, or $(CF_x)_n$, for $0.3 < x < 1.1$. Its lubricating abilities have been described as being better than or equivalent to graphite and MoS_2 (100,101). Although it has currently been tested only for terrestrial use, $(CF_x)_n$ does not require the intercalation of water vapor to lubricate as nonfluorinated graphite does (discussed in Section 5). Therefore, it could find application in the vacuum environment of space. However, it is uncertain if $(CF_x)_n$ offers enough advantages over MoS_2 to give it wide usage in vacuum/space (11). An example of its application is polyimide-bonded graphite fluoride coatings shown to double endurance and lower bearing torque in foil gas bearings during spinup and spindown cycles (102).

Advances are also expected in the understanding of solid lubrication mechanisms. Such understanding has proved elusive, but is crucial to optimizing the tribological properties of the films. For example, the mechanism of sputter-deposited MoS_2 friction/wear was described by one group as a "resupply" mechanism in which 80%-90% of film is worn in first 10% of life. The MoS_2 debris remains in the vicinity of the contact, providing a reservoir for subsequent lubrication (24). In contrast, another group has proposed a more classical layer-by-layer removal mechanism

(103). However, these studies represent different tribological regimes, reciprocal sliding and rolling element bearings, respectively. Future work should concentrate on developing a correlation of which mechanisms occur under the regimes seen in the full range of spacecraft applications of solid lubricants.

9. Summary

This report has illustrated many ways in which solid lubrication is crucial for moving mechanical assemblies on spacecraft. Liquid lubricants still cannot be replaced for devices operating at high speeds and with numerous cycles such as spin bearings. However, solid lubricants have filled many niches involving applications where containment of liquids is a problem, both from a contamination and a lubrication standpoint. Examples of such niches include deployment mechanisms (latches, rollers, and actuators), antenna gimbals, solar array drive bearings, and structural connections (rivets and screws). In addition, the use of solids to provide lubrication is critical for applications involving extremes of temperature. Two examples where low temperature lubrication is critical are scanner and gimbal bearings used with low-temperature infrared sensors, and cryogenic valves used on propellant tanks.

However useful solid lubricants have proven to be, their successful application requires planning and caution. The choice of the correct lubricant formulation and the development of successful lubricant application methods should be integral parts of the design of a lubricated device. Materials compatibility issues and the effect of debris generation on contamination and part tolerances must be considered. Adequate testing of the lubricated part should also be conducted, duplicating flight conditions as closely as possible. Also, care must be taken to minimize humidity and oxygen exposure during storage and operation of MoS_2-lubricated devices.

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